On Constructing Baby Universes and Black Holes

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Abstract

The creation of spacetimes with horizons is discussed, focussing on baby universes and black holes as examples. There is a complex interplay of quantum theory and General Relativity in both cases, leading to consequences for the future of the universe and the information loss paradox, and to a deeper understanding of quantum gravity.

General Relativity allows for a spacetime to have horizons, that is, spacetime regions that are inaccessible to certain observers. Due to quantum effects, horizons have novel consequences such as Hawking radiation from black holes [1], and "freezing" of quantum fluctuations in the inflationary vacuum [2]. These quantum effects are of fundamental importance and interest. Quantum fluctuations in inflationary cosmology may be responsible for seeding galaxies and cosmic large-scale structure, while Hawking radiation leads to the evaporation of black holes and to the information loss paradox. In this essay, we will discuss how to create two systems that have horizons, namely baby universes and black holes, the difficulties that are encountered in this process, and their possible resolution.

First consider the tantalizing possibility of creating a baby universe in a laboratory [3, 4, 5, 6, 7]. At the classical level all that we need do is to produce a large enough bubble of false vacuum, after which it will inflate and become a baby universe all on its own. This appears to be simple, but to successfully complete the process without the production of singularities, it can be shown that the process needs a matter source that violates the null energy condition. Classical matter sources that violate the null energy condition are not known to exist and, on the contrary, there are arguments to show that the existence of such sources would lead to unphysical consequences such as closed timelike curves. So a baby universe cannot be produced in the laboratory with (known) classical matter sources. This conclusion need not disappoint us, however, since the real world is quantum and even rather ordinary quantum fields can be shown to violate the null energy condition with no untoward consequences [8, 9, 10]. Perhaps quantum physics can be utilized to produce baby universes?

Imagine trying to produce a baby universe in a laboratory via the false vacuum bubble. The bubble will be connected to the laboratory by a wormhole, somewhat like an umblical cord as in Fig. 1. As long as there are null energy condition violating quantum fields present in the wormhole, the wormhole stays open. However, once the null energy condition violation ceases, the wormhole collapses, leading to a singularity, and the future evolution of the spacetime cannot be predicted. Since quantum null energy condition violations are short-lived, the existence, let alone the properties, of the baby universe cannot be calculated. Thus baby universes, with their horizons, cannot be shown to form in the laboratory, even when quantum effects are taken into account.

Baby universe production is closely tied to the initial conditions necessary for inflation. In inflationary cosmology, a region of spacetime undergoes super-luminal expansion within a

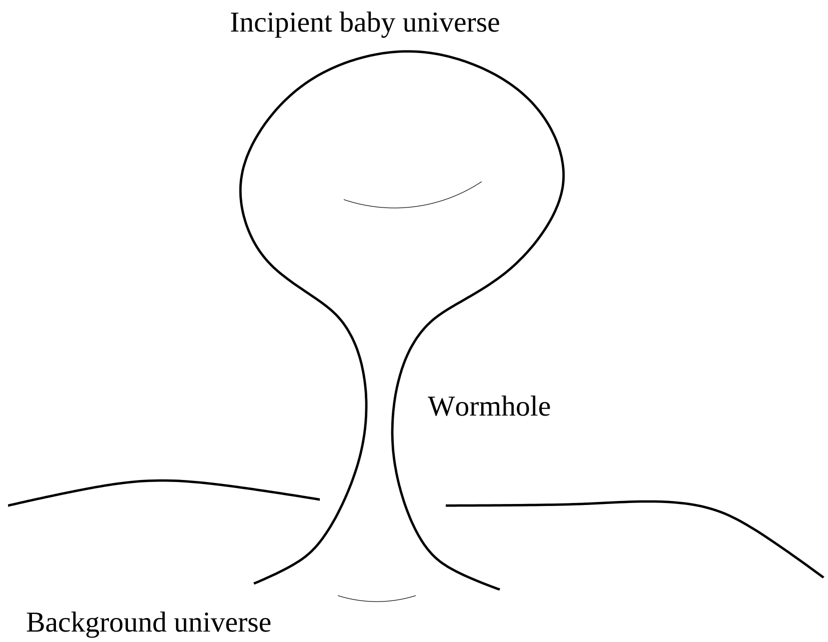

FIG. 1: Embedding diagram for an incipient baby universe connected to the background universe by a wormhole that needs null energy condition violating sources to keep it from collapsing and pinching.

background cosmology. If the inflating region is initially small compared to the background horizon, the process is very similar to the creation of a baby universe in a laboratory since effectively a bubble of false vacuum needs to be created that can then start inflating. Since we have seen that baby universes cannot be produced in the laboratory, it also implies that inflationary regions cannot be produced on sub-horizon scales, such as our laboratory. This implies that the false vacuum dominated bubble that grows by inflation and produces all the structure that we see, must start out larger than the initial horizon size [11]. The fact that the initial bubble has to be super-horizon size means that inflation must be preceded by a causation that extends beyond the light cone.

The argument showing that baby universes cannot be produced in the laboratory changes if quantum effects occur on a cosmological scale and the wormhole is as big as the background horizon. Then there is a pre-existing cosmological horizon and the expansion of the background universe can prevent the wormhole from collapsing and the concomitant singularities from forming. This is the basis of several cosmological models with eternal regeneration of new universes, such as in the eco-friendly "recycling universes" [12] and the minimalistic "island cosmology" [13]. These cosmological models reveal a new paradigm where cosmic

habitats and humanity are eternal, and provide an escape from the dreary conclusion that our universe has a bleak and empty future because of the accelerating expansion rate.

Horizons are also discussed in the context of gravitational collapse. At first sight, it appears that gravitational collapse inevitably leads to black hole formation which is accompanied by formation of an event horizon. However, here too, quantum effects play a subtle role during the collapse process, that may prevent the formation of an event horizon and possibly provide a resolution of the information loss paradox.

Before looking at the gravitational collapse problem, consider a more mundane problem where a spacecraft needs to deliver fuel to a distant destination like Mars. Suppose that the spacecraft only has a single tank for fuel, to be used for its own journey as well as to deliver to its destination. Then, as the spacecraft flies, it consumes the very fuel that is to be delivered. Further, the spacecraft can successfully deliver fuel to its destination, only if it burns less fuel on its journey than that initially contained in its tank.

Gravitational collapse is similar to the spacecraft's journey. Suppose there is a spherical shell of matter that is collapsing toward forming a black hole. Just as the spacecraft is on a journey to deliver fuel to Mars, the collapsing shell is on a journey to deliver mass to a central region that is compact enough to form a black hole. Again, in analogy with the spacecraft, the shell burns its mass and steadily loses energy due to quantum effects as it collapses [14, 15, 16, 17, 18, 19]. (The radiation is very similar to Hawking radiation but it does not require a black hole to be present.) In a slight departure from the analogy, as the shell evaporates, its mass gets smaller, and its "destination" moves further away since it needs to become even more compact to form a black hole. The shell keeps chasing its destination but possibly never gets there, as in a mirage [14, 16].

The General Relativistic problem is, however, a little more subtle than the spacecraft problem because there is freedom to choose coordinates, and in particular, the time slicing. Instead it is unambiguous to think in terms of observation of two different events, one signalling the evaporation of the collapsing wall and the other the formation of a black hole. The event signifying evaporation may be taken to be when an external observer, who is monitoring the emitted radiation, finds that all the initial energy of the shell has been burned up. The formation of a black hole may be signalled by the disappearance of some object. Then the question is if objects are observed to disappear before the total energy is burned up.

We know that the gravitational redshift of light emerging from a flashlight just outside a Schwarzschild event horizon is very large, and diverges in the limit that the flashlight approaches the horizon. Therefore, if the metric outside the shell, which is an incipient black hole, has the Schwarzschild form, then an object will never be seen to fall through the black hole event horizon by an external observer. Yet the external observer will collect the total mass of the gravitationally collapsing shell in a finite time, indicating that the shell burns up before a black hole is formed.

We have used the Schwarzschild metric to argue that an object falling into a gravitationally collapsing object is never seen to disappear. Using Birkhoff's theorem, the Schwarzschild form is inescapable. However, the Schwarzschild metric is derived from the classical Einstein equations, without taking quantum effects and radiation backreaction on the metric into account. In the case of the spacecraft bound for Mars, if we want to calculate the total fuel that will be burned, we should take into account the fact that the spacecraft gets lighter as the fuel is burned, and hence requires less fuel to accelerate. Similarly, as the collapsing shell loses mass, its collapse and the spacetime around it get affected. Although it is hard to see how the metric of the incipient black hole could be anything other than of Schwarzschild form, until the problem is solved including backreaction, we cannot really be sure that the black hole event horizon does not form, and we are left with the two possible spacetime pictures shown in Fig. 2. The first of these pictures is the conventional picture where burn out does not occur and a black hole is formed. An exciting aspect of the second picture where the shell burns out is that it resolves the information loss paradox in a very natural way [14].

It is quite remarkable how fundamental a role quantum physics plays in constructing systems with horizons. Any attempt at making baby universes and black holes, must face the constraints imposed by quantum effects and also utilize the opportunities offered by these very effects. To understand the "yin and yang" of quantum physics in spacetimes with horizons is to get that much closer to an understanding of quantum gravity.

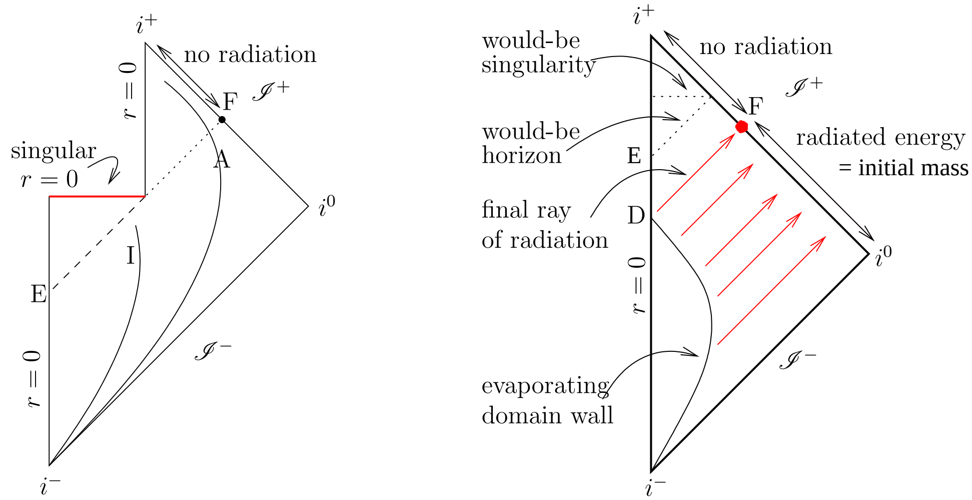

FIG. 2: A collapsing shell can either succesfully become a black hole leading to the spacetime picture on the left, or else it can burn up by pre-Hawking radiation and lead to the picture on the right. The picture on the left leads to the information paradox, while the picture on the right implies that no black holes are formed. It is also possible that the correct spacetime picture depends on the mass of the collapsing object.

Acknowledgments

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